New Measurement of (G_E/G_M) for the Proton

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Introduction

The structure of the proton is clearly a matter of universal interest in nuclear and particle physics. Charge and current distributions are obtained through measurements of the electric and magnetic form factors, G_E and G_M, and as such it is extremely important to determine these quantities as accurately as possible. In elastic e-p scattering magnetic scattering dominates at all but the lowest four-momentum transfer, Q^2, and therefore e-p elastic scattering differential cross section measurements leave G_M quite well established. For the very same reason G_E is much harder to determine but a recent, and probably ongoing, experiment in Hall A uses a novel and elegant polarization transfer method to measure G_E/G_M. This group has reported results up to $Q^2 = 3.47$ GeV^2 with an accuracy of ranging from about ± 0.03

at Q^2 = 1 GeV^2 to about ± 0.06 at Q^2 = 3 GeV^2 [1]. However, these results are in disagreement with previous experiments[2] in which G_E and G_M were extracted by a conventional Rosenbluth, or L-T, separation. The situation is summarized in Figure 1.

We propose to measure G_E/G_M for the proton in a region where the two previous determinations differ well outside of experimental error by utilizing the L-T separation technique in a new way in which only ratios of cross sections are used. Because of this the results are independent of target thickness and beam intensity and, furthermore, are relatively insensitive to uncertainties in beam energy and scattering angle. Counting rates are high and a statistical accuracy of less than 1/2% can be achieved in less than a day of data taking at each point. We propose to take data at three different beam energies and in a total of less than 4 days of data taking determine (G_E/G_M) at Q^2 = 1.4 GeV^2 to ± 0.03 and at 3.2 GeV^2 to ± 0.06.

Method for Determining G_{E_p}/G_{M_p}

The differential cross section for e-p scattering can be written:

$$\sigma(E,\theta) = \sigma_0(E,\theta)(G_E^2 + \epsilon^{-1} G_M^2 Q^2 \kappa)$$

where E is the incident electron energy, θ the electron scattering angle, σ_0 the Mott scattering cross section and any accompanying kinematic factors, $\kappa = (\frac{\mu_p}{2M_p})^2 =$ 2.212 and the magnetic form factor G_M is from now on in units of the proton magnetic moment μ_p. G_E and G_M are, of course, functions of Q^2 alone.

For a given E there is a one-to-one correspondence between θ and Q^2 and the cross section can be written:

$$\sigma(E, Q^2) = \sigma_0 G_M^2(\rho^2 + \epsilon^{-1} Q^2 \kappa)$$

where $\rho = \frac{G_E}{G_M}$.

For two energies, E_A and E_B, at the same Q^2 the ratio of the cross sections is:

$$\frac{\sigma(E_A, Q^2)}{\sigma(E_B, Q^2)} = K \frac{\rho^2 + \epsilon_A^{-1} Q^2 \kappa}{\rho^2 + \epsilon_B^{-1} Q^2 \kappa}$$

where K is a kinematic factor.

If at the two energies measurements are made simultaneously at two values of Q^2, Q_1^2 and Q_2^2, then there are two experimentally determined ratios:

$$R_A = \frac{\sigma(E_A, Q_1^2)}{\sigma(E_A, Q_2^2)} = K_A \frac{\rho_1^2 + \epsilon_{A1} Q_1^2 \kappa}{\rho_2^2 + \epsilon_{A2} Q_2^2 \kappa}$$

and

$$R_B = \frac{\sigma(E_B, Q_1^2)}{\sigma(E_B, Q_2^2)} = K_B \frac{\rho_1^2 + \epsilon_{B1} Q_1^2 \kappa}{\rho_2^2 + \epsilon_{B2} Q_2^2 \kappa}$$

and 2 ratios of physical interest:

$$R_1 = \frac{\sigma(E_A, Q_1^2)}{\sigma(E_B, Q_1^2)} = K_1 \frac{\rho_1^2 + \epsilon_{A1} Q_1^2 \kappa}{\rho_1^2 + \epsilon_{B1} Q_1^2 \kappa}$$

and

$$R_2 = \frac{\sigma(E_A, Q_2^2)}{\sigma(E_B, Q_2^2)} = K_2 \frac{\rho_2^2 + \epsilon_{A2} Q_2^2 \kappa}{\rho_2^2 + \epsilon_{B2} Q_2^2 \kappa}$$

note that $\frac{R_A}{R_B} = \frac{R_1}{R_2}$, or $R_1 = R_2 \frac{R_A}{R_B}$.

The idea of the proposed measurements is to pick one value of Q^2 (Q_1^2) where the recently reported $\frac{G_E}{G_M}$ from the polarization transfer experiment[1] is very different from the previously accepted values extracted from L-T separation measurements[2] and another Q^2 (Q_2^2) where $\frac{G_E}{G_M}$ must be close to its low-energy value of unity (with G_M in units of μ_p) and to pick energies such that ϵ_1 covers a wide range while ϵ_2 does not change a great deal. If, then, R_A and R_B are accurately measured and R_2 can be accurately calculated then R_1 is accurately determined. R_1 is a function of only ρ_1 ($=\frac{G_E}{G_M}(Q_1^2)$) and known quantities. We propose to do this at each of 2 values of Q_1^2, 1.4 and 3.2 GeV^2, with a common Q_2^2, 0.5 GeV^2.

Experiment

Kinematics

The proposed kinematics are shown in the accompanying table 1. There are several reasons why it is preferable to measure the protons rather than the electrons. First, the cross sections vary less rapidly with proton angle. In fact, at the highest (incident) energy, low Q^2 point it would be necessary to know the electron angle to .006^o in order to achieve a 1/2% accuracy. In contrast, only 0.022^o precision on the proton side is necessary in order to achieve the same accuracy. The smaller variation of cross section with angle also makes it possible to use a larger solid angle. In addition, the lab proton cross sections are larger at the low ϵ (i.e. large electron angle) points where the count rate is the lowest. Finally, the same Q^2 gives the same proton kinetic energy which means that each spectrometer makes its two measurements at the same Q^2 with the same settings. In fact, measuring the proton momentum provides a check that the data is being taken at the correct Q^2.

The kinematics have been selected to give a wide variation in ϵ at 2 values of Q^2 in the region where the two experiments give very different answers and also have a

Electron kinematics								
E_e (GeV)	Q^2 $(\text{GeV})^2$	ϵ	θ_e (deg)	K.E. (GeV)	$\sigma_e^{HallA}/\sigma_e^{SLAC}$	σ_e^{SLAC} (cm^2)	$\Delta\sigma$ %/deg	$\Delta\sigma$ $\%/(\%E_e)$
1.145	0.50	.755	41.276	0.879	0.972	3.902e-32	14.40	8.68
1.145	1.40	.099	122.020	0.400	0.990	1.451e-34	2.70	10.03
2.245	0.50	.938	19.314	1.979	0.969	2.179e-31	32.91	8.98
2.245	3.20	.120	108.490	0.541	0.989	5.752e-36	3.41	11.46
5.545	0.50	.990	7.494	5.279	0.968	1.617e-30	86.73	9.09
5.545	1.40	.964	13.170	4.800	0.921	2.669e-32	60.63	12.49
5.545	3.20	.870	22.350	3.841	0.929	3.410e-34	36.89	14.23

Proton kinematics								
E_e (GeV)	Q^2 $(\text{GeV})^2$	ϵ	θ_p (deg)	K.E. (GeV)	Momentum (GeV/c)	σ_p^{SLAC} $(\text{cm})^2$	$\Delta\sigma$ %/deg	$\Delta\sigma$ $\%/(\%E_e)$
1.145	0.50	.755	50.096	0.266	0.756	4.499e-32	13.17	4.21
1.145	1.40	.099	14.012	0.746	1.398	1.834e-33	4.06	4.01
2.245	0.50	.938	60.002	0.266	0.756	6.356e-32	18.55	4.67
2.245	3.20	.120	11.982	1.704	2.470	1.227e-34	5.32	4.42
5.545	0.50	.990	65.652	0.266	0.756	8.043e-32	23.16	4.97
5.545	1.40	.964	51.422	0.746	1.398	3.636e-33	20.76	6.10
5.545	3.20	.870	36.226	1.704	2.471	1.750e-34	19.10	4.29

Sensitivities			
E_e (GeV)	% ΔR_1 per % ΔE_e	Q^2 $(\text{GeV})^2$	R_1^{SLAC}/R_1^{HallA}
1.145	1.48	0.50	1.0041,1.0010
3.245	2.05	1.40	1.0749
5.545	1.48($Q^2 = 1.4$)	3.20	1.0646
5.545	2.46($Q^2 = 3.2$)		

Table 1: Proposed Kinematics.

low Q^2 with a small variation in ϵ. It is assumed that the linac runs reliably up to at least 1.1 GeV and that there can be up to 5 passes. The energies are such that the linac remains at 1.1 GeV with only the number of passes varied.

Spectrometers

The experiment could be performed either in Hall A or Hall C using the two spectrometers and the cryogenic target. The only special strains on either the target or the spectrometers are the precise angle determination, the ability to do the appropriate angle cuts (which may be an issue in the SOS) and the possible change in the y target acceptance as the spectrometer angle changes. The 4 cm liquid H target would be viewed at a maximum angle of 65 degrees and the angle only changes by a total of 15 degrees for the low Q^2 point. If necessary, an Aerogel detector will be used for pion rejection. Hall A appears to be preferable and it looks like the experiment may be easier to schedule in Hall A but Hall C would also be acceptable. Solid angles would be restricted to about 1 msr by a collimator and then further restricted by software cuts. Sieve slit data would be taken at each point and the spectrometers would be surveyed at each angular setting.

Yields

A beam of 25 μa on a 4 cm liquid hydrogen target gives a luminosity of 2.6×10^{37} which with a 1 msr solid angle means that the expected yields can be obtained by multiplying the cross sections in Table 1 by 2.6×10^{34}. This would mean 3 counts/sec or about 11000 counts/hr at the lowest yield point, $E_e = 2.245$ GeV, $\theta_p = 11.98^o$, and about 4.5 counts/sec at the other $Q^2 = 3.2$ GeV^2 point. The cross section is at least a factor of 10 higher at all of the other settings.

Checkout, calibration, beam energy measurement.	20 hours
Run at 1.145 GeV.	8 hours
Change energy to 5.545 GeV and move spectrometers.	5 hours
Run at 5.545 GeV.	6 hours
Survey the spectrometers.	6 hours
Move high Q^2 spectrometer.	1 hour
Survey the high Q^2 spectrometer.	4 hours
Run at 5.545 GeV.	20 hours
Change energy to 2.245 GeV and move spectrometers.	5 hours
Run at 2.245 GeV.	20 hours
Total	95 hours

Table 2: Beam Time Request

Systematic Errors

The measurement would be independent of beam current and target thickness. Dependence on angle is discussed above. An 0.1% change in beam energy translates into about a 0.2% change in high to low Q^2 cross section ratio though if it is an error in the entire energy scale (i.e. the energy being off by the same percentage at both energies) the error is even less. Finally, the proton momentum determinations further constrain the kinematics. A beam energy measurement would be made prior to each data set. The relative dead time corrections and efficiencies have to be controlled to 0.2 %.

Run Plan

Table 2 shows the proposed run plan for the experiment. Time for beam energy measurements is included in the energy change. A survey of the spectrometer angles before and after the data taking will be required.

Conclusions

With about 4 days of running time spread over 3 energies ratios which depend only on G_E/G_M for the proton can be measured to 0.7% ($\sqrt{2} * 0.5\%$ statistics and systematics) at two values of Q^2 where two major experiments that employ very different methods have reported qualitatively different results. At both Q^2 the predictions from the two experiments of the ratio that is to be measured differ by about 7%, or 7 times our expected uncertainty.

References

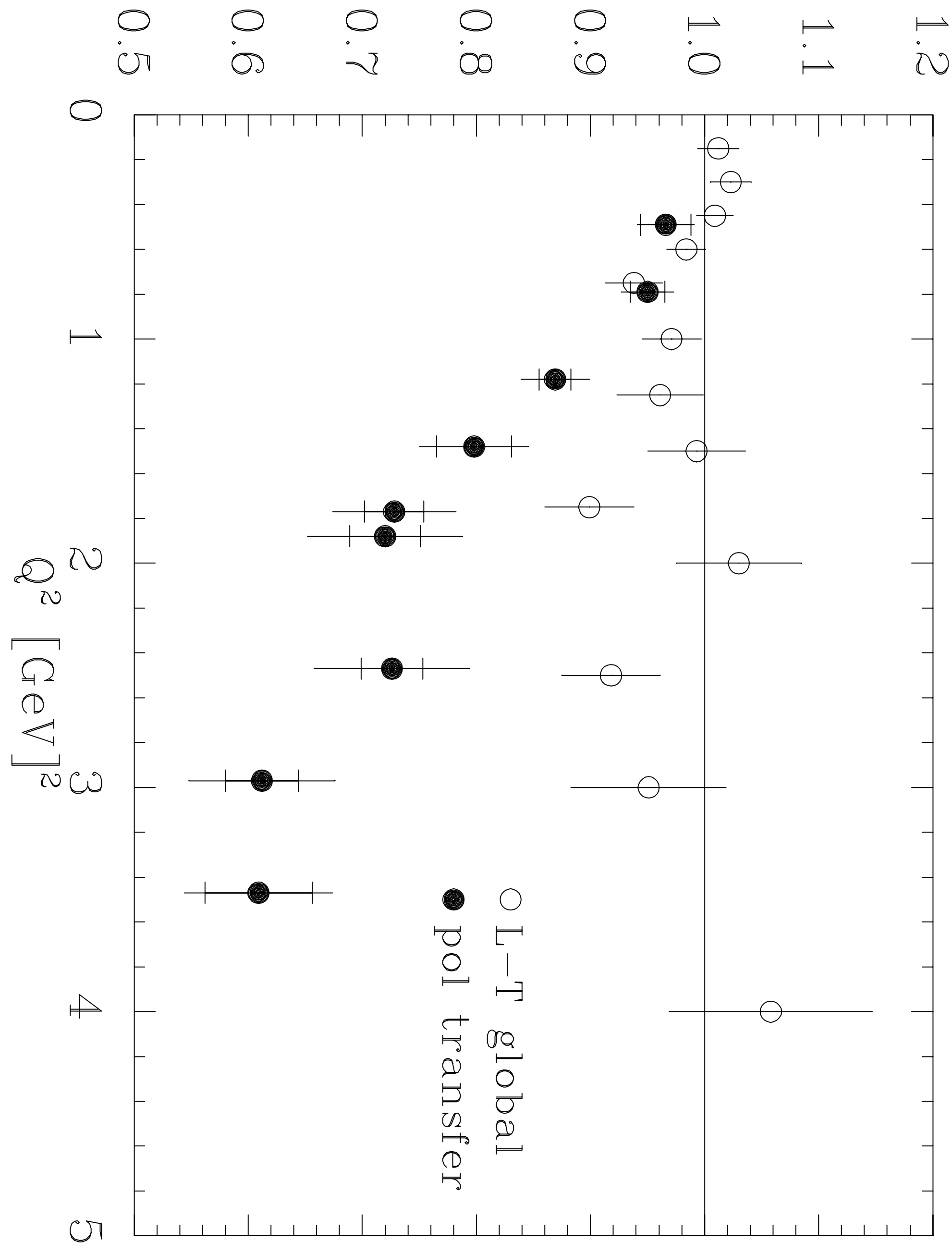
1. M. K. Jones *et. al.* Phys. Rev. Lett, **84**, 1398 (2000).

2. R. C. Walker *et. al.* Phys. Rev. **D49** 5671 (1994) and references cited therein.

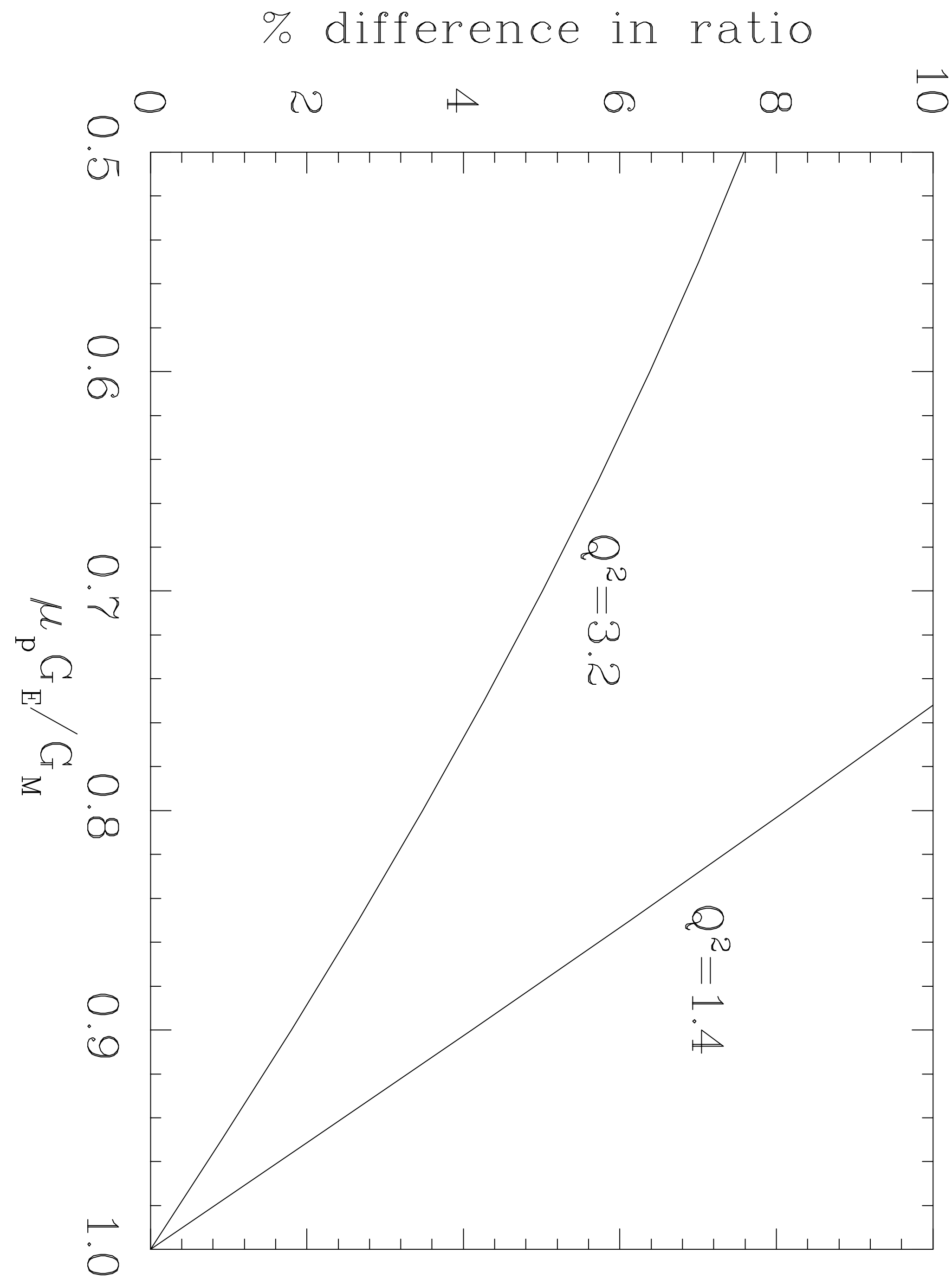
Figure Captions

Figure 1: $\mu_p G_E/G_M$ as deduced from polarization transfer (ref. 1, closed circles) and L-T separation (ref 2, open circles) experiments. The outer error bars are the total uncertainty, while the inner error bars (for the polarization transfer) are the statistical uncertainty.

Figure 2: Variation of the ratio to be measured as a function of $\mu_p G_E/G_M$ at the 2 values of Q^2. Reference 1 reports about 0.8 at $Q^2 = 1.4$ GeV^2 and about 0.6 at $Q^2 = 3.2$ GeV^2.



$\mu_p G_E/G_M$
Q^2 [GeV]^2
L−T global
pol transfer
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
0
1
2
3
4
5


% difference in ratio
0
2
4
6
8
10
0.5
0.6
0.7
0.8
0.9
1.0
$\mu_p G_E/G_M$
Q^2=3.2
Q^2=1.4